Modelling Requirements for Bulk Power System Reliability Evaluation

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ABSTRACT

Modelling requirements for bulk power system reliability evaluation are presented. Three models are proposed to quantify the reliability considerations related to capacity, reserves, and stability.

KEYWORDS

Reliability modelling, transmission reliability, composite system reliability.

1.0 INTRODUCTION

A computer program capable to evaluate the reliability of the bulk power system in a way which can be effectively interpreted in terms of the real system to aid the transmission design problem, is without doubt very valuable. Considerable effort is being spent on the development of such a program. Conceptually, the computational algorithm required is simple and consists of four main steps, namely:

1. Selection of power system states.
2. Simulation of the operating conditions which in real life would exist in each of the selected states.
3. Evaluation of the operating conditions within each state with respect to predefined performance criteria.
4. Aggregation of the results of the evaluations to generate reliability indices.

From the computational burden viewpoint, the practical implementation of the above procedure poses formidable problems, especially the implementation of the second step. Simplifications in the models can be used to reduce the computational burden. However, it is essential to ensure that these simplifications have not gone past the point where the models are no longer sufficiently representative of the real system to permit meaningful utilization of the results for practical design decisions.

The objective of this paper is to identify the factors that need to be modelled to ensure realistic simulation of the system operating conditions. The factors needed are extracted from a discussion of the system behaviour and operating requirements. Based on this discussion, it is proposed that the reliability evaluation problem can be decoupled into three considerations, each of which can be addressed with a separate model.

2.0 POWER SYSTEM BEHAVIOR AND MODELLING IMPLICATIONS

The power system never reaches a true steady state. Changes are continually injected into the system which reacts immediately with physical time constants which vary from a few microseconds to a few seconds. In the wake of these reactions various automatic and manual controllers are continually hurrying to operate on the system to keep it in motion towards acceptable operating conditions. These changes are due mainly to load changes, equipment failures and operator actions.

Within the context of system state enumeration, a new state is entered every time the load changes, or equipment fails, or equipment is repaired. The system behaviour existing over the duration of a state, will in general vary from transient, immediately following state entrance and for a few hours after, to steady state. The correct characterization of the system conditions over the duration of a state is critical to the correct simulation of the power system for reliability evaluation. Within the context of this discussion, the terms 'transient' and 'steady state' are defined as follows.

A. Transient Behavior

Transient behavior exists when the power system conditions at any one time are determined by one or more of the following:

1. Transient and dynamic characteristics of system equipment.

2. Operation of automatic system controllers following equipment failure.

3. Unplanned manual operating actions.

4. Equipment deployment for operation is constrained by that allowed by the operating reserves policy and by all scheduled maintenance.

B. Steady State Behavior

Steady state behaviour exists when the power system conditions are entirely determined by the implementation of an operating plan prepared sufficiently ahead of operating time such that:

1. The operating plan, and thus the power system conditions, are fully consistent with predefined operating procedures.

2. Equipment deployment for operation is constrained only by equipment which is failed or which cannot be recalled from maintenance.

State enumeration and simulation of system conditions within each state for the above two behaviours has very significant differences.

At any one time, the operating conditions of the system during a transient are strongly dependent on the conditions existing just before, that is, on initial conditions. This has two key modelling implications, namely:

A1. Correct simulation of the operating conditions following state entrance cannot be done without determining the operating conditions just before. Therefore, state enumeration must consider:

- i. All possible system states determined by the up/down status of its components.
- ii. For each state 'k' in (i), all the possible states from which state 'k' can be entered.
- iii. For each combination from (i) and (ii), all the significant possible times at which the combination can exist.
- iv. For each situation in (iii), all the possible failure mechanisms.

A2. Correct simulation of the operating conditions throughout the period characterized by transient behaviour must recognize the time sequence and duration of events. As an example, the time required to formulate and implement manual corrective strategies must be recognized.

Very significantly, the operating conditions of the system during steady state are totally independent of initial conditions. This has two key modelling implications, namely:

B1. State enumeration must consider only the possible system states determined by the up/down status of its components.

B2. Simulation of the operating conditions for the duration of the steady state period, can assume that all events occur instantaneously. In addition, the operator can be modelled with infinite wisdom in the sense that in any one state, the available resources always exist organized in an optimal manner within the constraints of installed capacity, failed equipment, equipment which cannot be recalled from maintenance, and predefined operating procedures.

3.0 SYSTEM BEHAVIOUR AND MODELLING FOR STATES ENTERED VIA FAILURE

From the moment a new state is entered as a result of equipment failure to several hours later, the system conditions are characterized by transient behavior. After this initial period, the conditions will achieve steady state. Of course, this is possible only if the duration of the state is long enough.

The transitions through the various conditions from transient to steady state are continuous. For the purpose of characterizing these conditions for modelling purposes, it is useful to divide the transitions from transient to steady state into four periods as follows:

1. A period Ta from state entrance up to about three minutes after.
2. A period Tb from three minutes to about thirty minutes after.
3. A period Tc from thirty minutes to about seven hours after.
4. A period Td spanning the time in excess of seven hours after the failure.

Each one of these periods is discussed below.

3.1 Behavior and Modelling Requirements for Period Ta

During this time the system conditions are characterized by transient behaviour. These conditions are changing fast and they are determined by the system electro-mechanical responses, operation of automatic controllers, and the system conditions prior to state entrance. Power flows and voltage changes are due to factors such as: inertial phenomena; equipment loss due to protective relays; load shedding due to under-frequency protection; load and generation rejection schemes; spinning reserves deployment via governors and automatic generation control. An important realization is that during this time no manual operating action is possible because there is not enough time.

The modelling requirements are considered to be:

a. The simulation to compute flows, voltages and frequency must be done with the models currently used for short-term and long-term stability computation.

b. State enumeration must be done consistent with Item (A1) in Section 2.0, and the simulation in (a) above must be repeated for each state.

It is clear from the above that a fully probabilistic evaluation of system conditions over period Ta poses a formidable, and likely impossible, computation burden.

3.2 Behaviour and Modelling Requirements for Period Tb

The beginning of this period marks the approximate point in time at which the operator enters the picture as a controller. And in fact, during this period, operating conditions are determined by largely unplanned, manual operating actions, such as:

a. Generation rescheduling. This would be limited to the synchronized reserves, fast start generating units, and pre-arranged emergency interconnection transactions.

b. Operation of phase shifters.

c. Manual system sectionalization, removal of overloaded apparatus, and load shedding.

It is clear from the above, that the operating conditions during this period are also characterized by transient behaviour. The modelling requirements are considered to be:

a. The simulation to compute flows and voltages requires solution of the ac load flow. Several snap-shot solutions, performed chronologically, would be required to cover the period.

b. Analysis must be done for each situation studied in the previous period. In fact, the system conditions emerging from the previous period provide the initial conditions for this period.

c. Several factors must be represented such as: time dependence of transmission ratings; recognition of loading rates of thermal generators; load variation with time; equipment scheduled maintenance; predefined emergency interconnection transactions; time to formulate and implement operating actions; the fact the generation available for rescheduling is limited to the amount allowed by the operating procedures.

Two key items emerge from the above. One is that the time sequence and dependence of events must be recognized. Thus reliability evaluation for this period will require a chronological simulation. The other is that it is essential that operating procedures be modelled since these determine: (i) the amount of resource available to the operator to steer the system on a safe course; (ii) the direction in which the operator will aim the system.

3.3 Behaviour and Modelling Requirements for Period Tc

At the beginning of this period the resources available to the operator for system control are still restricted to those specified by the operating procedures being used. Towards the end of the period, about seven hours after state entrance, almost all installed resources are available. The significance of the seven hours is that within this time cold thermal units can be brought to operating status.

The modelling requirements for this period are essentially the same as for the one prior. The additional modelling considerations are: (i) as time progresses, the operator is increasingly freed by the restrictions of the initial conditions. For example, more time is available to ready additional generation for rescheduling. (ii) Economic dispatch must be recognized as this determines the directions in which the system will be steered. (iii) Operating procedures will have to be modelled since they determine the objective operating status for the system.

3.4 Behavior and Modelling Requirements for Period Td

This period extends onward from about seven hours after state entry. During this period the system conditions are characterized by steady state behavior, and the modelling implications mentioned in Section 2.0, items (B1) and (B2) apply here. Steady state is blessed by timelessness. This affords a significant simplification in the modelling requirements compared to those for the prior periods.

The modelling requirements are considered to be:

a. State enumeration based on the up/down status of system components. It will be shown later on that transmission failures do not have to be modelled to achieve acceptable results.

b. Load flow solution for each state.

c. The resources available within each state are to be organized to achieve operating objectives in an optimal manner. This requirement is a blessing in disguise. In fact, each state potentially can exist in an infinite number of load flow conditions. But optimality will restrict analysis to only one.

3.5 Concluding Remarks

From the discussion in the preceding four sections, it is evident that state analysis for reliability evaluation cannot be done correctly by representing the states with average durations. Furthermore, the statistical analysis to compute the failure probability data must recognize the need for separating state duration into several periods. For example, in evaluating the probability of a state 'k' in the steady state, it makes no sense to include encounters of state 'k' that last less than seven hours. In this context, it is of interest to note the difference between state entrance due to failure and state entrance due to repair. With two exceptions, every state can be entered either via failure or via repair. The two exceptions are the state with all equipment up and that with all equipment down. Entrance via failure results in a transient, while entrance by repair does not, since the repair process is fully planned. Therefore, the operating conditions within a state entered via repair exhibit steady state behaviour for the entire state duration.

Based on the above discussion, the algorithm for reliability evaluation as described in Section 1.0 would be too complex and cumbersome and, likely, impossible to develop. An alternative is to separate the reliability related considerations at system planning time into weakly interdependent considerations, and address each of these with a separate model. The remainder of this paper identifies these separate models.

4.0 RELIABILITY RELATED CONSIDERATIONS AT SYSTEM PLANNING TIME

The power system design must permit achieving the operating objective of meeting the load with satisfactory quality of service at minimum cost. The term quality refers to acceptable voltage and frequency as well as acceptable continuity of supply. The operating conditions observable on the system at any one time represent the implementation of an operating plan initiated months in advance of operating time. The preparation of this plan is based on:

(a) Forecast of the load

(b) Forecast of equipment availability.

As time progresses towards operating time, the plan is continually adjusted consistently with the latest information available. The operating plan in essence consists of:

1. A list of the generating units to be used to meet the load at different points in time.

2. A list of equipment and the time at which they would be outaged for maintenance.

The above plan reflects the load forecast and equipment availability expectations based on the knowledge at the time the plan is prepared, and must contain a safety margin which will provide the operator sufficient maneuverability to operate in the face of unexpected failures and load forecast errors without diminishing the quality of service to the point where it would become unsatisfactory. This safety margin is provided by planning to have a reserve of system equipment capacity available for operation in excess of that strictly needed to meet the load. This reserve is planned for both generation and transmission. Of course, the more the reserve, the higher would be the severity of the failures that could be faced without affecting supply, and vice-versa.

As discussed above, following an equipment failure, the system goes through a transient. During this time, the system can remain stable or not. Therefore, there is an additional constraint on the reserve value needed, namely, that it must permit system operating modes which guarantee a stable transition from the pre-failure to the post-failure steady state conditions for some predefined set of contingencies. This contingency set is chosen to insure that the incidence of instability is consistent with the perception of what is satisfactory quality of service.

With reference to the discussion in Section 3.0, the portion of a state duration beyond about seven hours is characterized by operating conditions determined by operating actions planned well in advance of operating time, namely, consistent with the plan just discussed. The operators have no control over approximately the first three minutes after a failure. The period between three minutes and seven hours represent the time over which the operator may be forced momentarily away from the operating plan and during which the operating reserves are utilized to avert load cuts or other undesirable impacts. The first three minutes after a failure represents the time over which the capability of the system to transit in a stable manner from pre-failure to post-failure is being called upon.

On the basis of the above discussion, the design considerations related to reliability at system planning time are:

I. Capacity Adequacy Consideration

Is the total generation and transmission capacity sufficient to meet the load and the operating reserve requirements with due recognition of scheduled and forced maintenance.

II. Reserve Adequacy Consideration

Is the amount and response of the operating reserves in accordance with a given policy, suitable to avert sufficiently load cuts and other undesirable impacts in the face of the unexpected events that actually occur.

III. Transient Performance Adequacy Consideration

Is the system operable so that, in the face of actual failure events, the incidence of pre-failure to post-failure transition instability is acceptable.

5.0 RELIABILITY MODELS FOR RELIABILITY EVALUATION FOR PLANNING PURPOSES

At any one point in time, if there were no unexpected events in the seven hours preceding that point, the system operating conditions would be exactly as planned seven hours before. However, if unexpected events were to occur, the operating conditions would deviate from the planned course momentarily. The severity of the plan deviations would be dependent on the severity of the unexpected event. The operator would, however, immediately initiate a control process aimed at bringing the system conditions back in line with the operating plan. Such plan, of course, is continually evolving on the basis of the latest information on equipment availability and load prediction. Accordingly, the system conditions can be visualized consisting of two components, namely:

(a) A long term or steady state component which describes the operating conditions in terms of the operating plans formulated about seven hours ahead of time.

(b) A short term or transient component which is superimposed on the steady state component. This transient component results from unexpected changes in the system such as in equipment availability and load prediction after the plan is formulated.

Within the context of reliability evaluation, the steady state operating component in (a) will result in load cuts or other undesirable impacts only as a result of shortages in the capacity of the generation or of the transmission. Consequently, a probabilistic analysis utilizing a model which recognizes the steady state operating component only, can address the question of system capacity adequacy.

The short term component, however, can result in additional load cuts or other undesirable impacts due to:

1. The particular operating procedures which are being utilized, especially those related to operating reserves.

2. The system transient performance. This depends on the system design as well as on the operating procedures being utilized.

It is important to notice that the load cuts or other undesirable impacts due to the steady state operating component are not a function of operating procedures. As an example, the operator would like to operate the system so that single contingencies can be withstood without loss of load or of service quality. However, he will not cut load to maintain such operating margin. Similarly, the operator aims at the most economic dispatch, but he will not cut load to achieve it.

A model which simulates the short term operating component is useful to evaluate:

(i) The reliability consequences of contemplated operating procedures.

(ii) The transient performance adequacy within the context of the design and of the contemplated operating procedures.

The response of the system and of the automatic controllers over the first three minutes following an initiating failure event, determine the up/down state of the components which were in operation just before the initial failure and also determine the system load flow conditions which the operator has to start dealing with. These conditions can either be catastrophic and totally unexpected if the system were to be unstable or, if the system were to remain stable, would be in accordance with the designed performance of the automatic controller, such as relays, automatic generation control, and governors.

From the above discussion, three system models are identified, namely:

A. A steady state model (SSM). This model simulates operating conditions as they would exist if the operating plans prepared about seven hours ahead of time were to be implemented in the absence of unexpected events. Thus, the system operating conditions would be determined by operating actions planned well ahead of operating time. This corresponds to the model necessary to simulate the system over the state duration period beyond seven hours. This model would be suitable to evaluate the generation/transmission capacity adequacy to meet the load and the capability to provide the operating reserves in accordance with contemplated operating policies. The modelling requirements for this model are the same as those for period Td, presented in Section 3.4.

B. A transient model for stable (TMS) transitions. In this model, the analysis over the first three minutes would identify the equipment and load that gets disconnected over this period, and thus define the system which the operator has to start dealing with, within the constraints of equipment available for operation in accordance with the operating plan as it stood at the beginning of the failure. For the remaining time up to about seven hours, the model would simulate the system conditions consistent with operator remedial actions constrained by the equipment availability limitations as per current operating plan. Thus this model would address the adequacy of the operating reserves policies in the face of actual unexpected events. The modelling requirements for this model are the same as those for periods Tb and Tc presented in Sections 3.2 and 3.3.

C. A transient model for unstable (TMU) transitions. This model would simulate system behavior over the first three minutes from the initiating failure event and identify the incidence of instability. Thus, this model would address the system design adequacy related to stability within the context of contemplated operating policies. The modelling requirements for this model are the same as those for period Ta presented in Section 3.1.

6.0 TRANSMISSION MODELLING REQUIREMENTS

This section addresses the extent to which transmission failure has to be modelled. The bottom line is that if the answers sought are impacted significantly by the failure of transmission, then it obviously needs to be modelled. But if the impact on the answers are not significant, then there is no point in complicating the model.

There is no question that transmission failure and scheduled maintenance significantly impacts system operation over approximately the first seven hours following the failure. This is the time over which the capability of the system to remain stable is called upon, and during which the safe operation of the system rests squarely on the adequacy of the operating reserves. But do transmission failures and scheduled maintenance impact significantly on planned operation?

It is clear that a transmission failure which results in successful reclosure ten seconds after fault occurrence, has no impact on the long trend operation of the system. Its only impact is the superposition of transient power flow fluctuations over the system. Consideration of such failure is meaningful only when trying to establish the capability of the system to remain stable under fault conditions. As the duration of the outage becomes longer, the picture becomes more complicated. However, it is clear that in the failure aftermath, the system will achieve safe conditions provided the transmission and generation reserve is adequate. And certainly, if the outage lasts say, six hours, this outage does not impact on the operating plan scheduled for implementation seven hours later.

To get a feel for the importance of modelling transmission failures in the SSM model, which addresses planned operation, transmission failure data was analysed. The statistical analysis consisted of simulating the evolution of the operating plan, based on current knowledge, for a point in the future remaining always seven hours ahead of actual operating time, and accumulating the amount of time that the plan at this future point had to consider different numbers of transmission circuit out of service. The result of this analysis showed that to address the transmission and generation capacity adequacy question with reasonable accuracy, there is no need to model transmission failures.

Another aspect of transmission modelling which is relevant, is transmission scheduled maintenance. In this respect, it is noted that:

(a) Transmission scheduled maintenance outages are taken when the impact on the system in terms of cost and unreliability is negligible.

(b) If the occurrence of unexpected events overlap maintenance outages and the situation were to result in a significant danger to load supply security or a significant increase in the operating costs, the scheduled maintenance outages are generally recallable within seven hours.

On the basis of this, it was concluded that scheduled maintenance outages do not have a significant impact on the evaluation of reliability and costs resulting from the planned operation of the system.

7.0 CLOSURE

Space has not permitted a more complete development of the thoughts presented, and has not permitted detailed definitions of the models proposed. It is hoped, however, that the discussion presented provides a useful input towards the development of credible models for bulk power system reliability evaluation.

Based on the thinking process presented here, additional work was done and the details of the Steady State Model (SSM) were developed. The resulting model was implemented in PROCOSE, a computer program currently being used for composite reliability and other probabilistic evaluations. In its current form, this program can represent up to 2000 buses. The computational algorithms implemented in this program were presented in Reference (3). An additional paper describing the program in its current form is planned. Although work is continuing, to date the definitions of the TMS and the TMU models are not yet complete.

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Discussions

J. Endrenyi and L. Wang, Ontario Hydro, Canada It is not quite clear whether the models discussed in this paper are meant to assist system planning or operating. The models covering a period shorter than seven hours seem to be in the latter category. In this short time interval, it is conceivable that transmission failures have negligible probability (but far from negligible effect). In the SSM model, however, transmission failures cannot be neglected - contrary to the author's conclusion in Section 6. His observation is based on statistics collected "seven hours ahead of actual operating time" (no surprise that transmission failures do not appear within such a short interval), whereas statistics for a steady state model should be collected over the long-term. If the task is the assessment of transmission system adequacy, transmission line failures obviously cannot be neglected; nor can their impact be disregarded in the TMU model. Incidentally, how was 7 hours selected as the time that separates the ranges of the TMS and SSM models? The author's comments on these remarks will be appreciated.

E.G. Neudord, Ontario Hydro, Canada I would like to congratulate the author for writing this paper because I am sure it will generate a lot of useful discussion. In the past 10 years, there has been a lot of work done on establishing the modelling requirements for bulk power system reliability evaluation. Despite this, there is not real consensus on what these requirements should be. This is especially true in the area of transmission reliability evaluation. I believe that this paper may be helpful in reaching a consensus on modelling requirements for reliability evaluation.

I have the following comments on this paper:

1. I fully agree with the author that it is not possible at the present time to determine the transient component of bulk power system reliability. This problem is very complex and we lack the required models, much of the data that would be required and the computing power that would be required.

   For example, I will elaborate on some of the parameters that would have to be considered in determining whether transitions from state to state due to failure are stable or not. This would involve solving the transient stability problem in a probabilistic manner. The following are some of the parameters that would have to be considered.

   - load level
   - generation schedule
   - transmission network state (are all elements in-service or are these elements out of service due to forced or planned outages)
   - element that is faulted
   - location of fault
   - type of fault
   - clearing time, etc.

In order to determine the probability of instability, all of these parameters would have to be varied. This would result in a large number of stability cases to be run. In order for such testing to be feasible, it will be necessary to speed up solution times by a couple of orders of magnitude. It is obvious that we are not able to solve this part of the problem at the present when one considers that a large system has to be represented in order to get acceptable results (example - 2000 buses).

Since transient stability analysis is an important part of transmission planning, it is therefore, not possible to use a probabilistic method to do transmission planning. The electric utility industry has developed deterministic testing methods in order to do this. Stability tests are performed with a severe set of load and generation conditions. In this way, many less severe conditions are accounted for without actually testing for them. The deterministic method uses a predefined set of contingencies.

The fault is usually applied at the most critical location on the most critical line. Here again, this method accounts for many less severe faults without actually testing them.

In summary, while it is not possible to use probabilistic methods to plan transmission systems, the industry is very successfully using deterministic methods to adequately plan the transmission system.

2. *I also agree with the author that the steady state model is suitable for determining the unrelability contributions attributable to generation capacity.*

   It is interesting to note that in the evaluation of generation reliability, all outages are usually considered, whereas, the paper would exclude outages which have a duration of less than 7 hours. For longer outages, the total outage duration is normally used, whereas, the paper would not use the first 7 hours of an outage in the preparation of data.

   The model used in generation reliability evaluation is valid because most generator outages are of fairly long duration (example - longer than 7 hours).

The effect of transmission limits can also be included in determining capacity requirements with the steady state model. However, it will be necessary to determine these limits outside the reliability program by performing studies using the deterministic criteria.

<u>S.J. Argent, CEGB, England</u> 1. *I like the broad philosophy of separating system reliability into time related component parts. If such an approach is practically implementable, it would allow the system planner to know how much investment is justified by either "capacity", "reserves" or "stability" considerations. Can the author estimate the proportions of the overall investment in <u>transmission</u> justified by each of the three components of system reliability? In particular, does "capacity" dominate?*

2. *What reliability indices are produced by the three conceptual models (e.g. LOLE or LOEE) and would these eventually be linked to some nominal "cost of energy not supplied" when making transmission planning decisions?*

<u>Author</u> *I would like to thank the discussers for their interest in the paper.*

In reply to Mr. J. Endrenyi and Mr. L. Wang, I have the following comments. As I state in the paper, the discussion is presented within the context of bulk power system planning. However, the TMS and the TMU models would be useful for operating also. At planning time, the planning engineer can change the design of the power system to affect any or all of the three reliability related considerations of capacity, reserves, and transient performance. At operating *time, however, the system generation and transmission capacity is fixed in amount and type. With minor exceptions, the only thing that can be done to affect reliability is to consider different operating modes and operating procedures. Accordingly, only the TMS and TMU models would be useful for operating.*

I state in the paper that the modelling of transmission failures is very important for the TMS and TMU models, but not important for the SSM model. These discussers appear to have been confused by the reasoning present in the paper and I apologize for not presenting the discussion in a more clear manner. To answer their question properly, I would have to reiterate most of the material in the paper, and therefore I would like to refer them to the paper. The significance of the seven hours is explained in the first paragraph of Section 3.3. These and other discussors, and the thrust of current development effort have convinced me that a clear understanding of why to model or not to model transmission failures is essential, and I have started working on a paper expanding on the statements made in this paper.

In reply to Mr. S.J. Argent, I have the following comments. My proposal to divide the composite reliability problem into three components was motivated by the conviction that only such an approach can be successful. As he mentions, it would also permit the planner to see what is the result of his investigation in terms of capacity, reserves and stability considerations. I do not know how to answer his other questions in a meaningful manner in the few words that I am allowed here.

I am in general agreement with the points made by Mr. E.G. Neudorf.